Corte Madera Innovative Wetland Adaptation Project: WHAFIS Wave Attenuation Modeling

1 Introduction

This portion of the wetland adaptation study investigated wave attenuation by marshes in order to quantify the flood protection benefits of tidal wetlands along the Bay margin. The study explored the sensitivity of wave attenuation to parameters such as the profile of the mudflat and marsh; the presence, slope and position of the scarp; the vegetation species that colonize the marsh; the incident wave height and still water depth.

Sea level rise (SLR) will worsen flooding in two ways – the increased water levels themselves and the increased hazard due to waves propagating across the increased water levels. Wave hazard increases both because the waves are higher (hence closer to levee crests and other flooding barriers) and because waves propagating across deeper water experience less dissipation from the bed. Because dissipation is reduced for deeper waters, more wave energy arrives at the shoreline. Loss of wave energy by frictional bed dissipation is an important process through which mudflats and marshes attenuate waves. Mudflats and marshes are shallow geomorphic units created by the interplay of waves, currents, sediment, and biota which set the bed elevation in the nearshore of many estuaries. In the shallow water of mudflats and marshes, waves attenuate as they propagate toward the shoreline. In addition to the attenuation of wave energy due to bed friction between wave currents and vegetation's stems and leaves causes additional attenuation of wave energy.

To estimate wave attenuation provided by mudflats and tidal marsh vegetation, we developed and applied the WHAFIS wave model (FEMA, 1988), as described in this volume. This model enables the investigation of the sensitivity of wave attenuation to water levels (e.g., SLR), wave conditions, bed geometry, and vegetative cover. Besides characterizing present and future wave attenuation, the modeling informs the selection and design of management measures intended to preserve the mudflat and marsh flood protection benefits.

The wave modeling will specifically address the following questions:

1. What are the mechanisms that attenuate wave energy across typical wetland profiles in Corte Madera Bay that are representative of other Bay shores;

2. What wave conditions are predicted for forcing conditions in present day and in the future?

3. What is the relative impact of WHAFIS input parameters (both changes in bed geometry and hydrologic boundary conditions) on model predictions of wave attenuation?

2 Methodology

This section describes the WHAFIS model and the inputs and parameters it uses to estimate wave attenuation.

2.1 Model Description

The WHAFIS (Wave Height Analysis for Flood Insurance Studies) model was developed by FEMA to predict wave conditions associated with storm surge (FEMA, 1988). The model is one-dimensional (1-D), in that it predicts wave height and period along a transect perpendicular to the shoreline. The model uses the conservation of wave energy equation to calculate wave height growth or attenuation resulting from the balance between wind generation and wave dissipation by marsh plants. Dissipation through marsh plants is mainly the result of the drag force generated between the marsh plants and the currents induced in the water column by the passing waves. Inputs in the latest version, Version 4.0, include bed elevations, water level, initial wave height and period, wind speed, and vegetation parameters (Divoky, 2007). The model outputs wave heights, wave periods, and wave crest elevations at locations along the transect.

Note that WHAFIS does not include bed friction over mudflats, so cannot be used to predict wave attenuation over this region. Options for estimating attenuation over mudflats include simple friction factor methods (FEMA 2005, Jonsson and Carlsen 1976). Recent wave data and ongoing analysis by the USGS shows promise regarding the selection of appropriate friction factors for San Francisco Bay (J. Lacy, personal communication). Alternatively, a more sophisticated shallow water wave model such as SWAN can be used (Delft University of Technology, 2012). As described in Section 3.6, SWAN demonstrated good agreement with wave attenuation data collected as part of this project.

2.2 Model Parameterization

Setup of the WHAFIS model requires selecting values for bathymetry, water level, waves, and vegetation to represent conditions in San Francisco Bay (Bay) and Corte Madera Bay. Figure 1 shows a representative cross-section of model parameters. The parameter set was developed in conjunction with the SWAN modeling effort to make the model set up as similar as possible between the two models. Output from the WHAFIS model was verified in the sense that the predicted wave attenuation is consistent with a general understanding of wave attenuation observed at other marshes and consistent with the wave attention predicted by SWAN (Section 3.6). Ideally, the model would be calibrated[1] and validated[2] by comparing its predictions against observed wave conditions in Bay marshes. However, no known San

[1] Calibration refers to the process of adjusting model parameters so the predicted output more closely matches observed values.

[2] Validation refers to comparing the calibrated model to a different data set to quantify the parameterized model's skill at predicting observed vales over a broader range of conditions.

Francisco Bay wave data within marshes was available for this study to use for calibration and validation.[3]

References and sources for model input parameters are described in detail in the sections below.

2.2.1 Water Level

The WHAFIS model runs considered six water levels that span the expected water levels for existing conditions and predicted SLR. These water levels were used to determine sensitivity of the model to both existing and future SLR conditions, and were based on several data sets (NOAA tide gages at San Francisco[4] and Richmond[5]), San Francisco Bay flood analyses (USACE, 1984; DHI, 2011), and the NRC (2012) sea level rise assessment.

Based on these sources, this study considered water levels ranging from 6 ft to 11 ft NAVD at one foot increments. The range of expected water levels for existing and future SLR conditions are summarized in Table 1. To assist with interpreting each water level and SLR scenario pairing, an event and return period are presented as a reference point. For example, under existing conditions, a 7-ft water level is interpreted as the peak during spring tides, an event that occurs approximately every two weeks. Note that these interpretations are not exact mappings in that the events are rounded to the nearest foot and the return periods are representative of statistical analyses. Note that the 2050 and 2100 SLR projections are based on NRC (2012)[6] for San Francisco Bay, which are 11 inches and 36 inches of SLR for 2050 and 2100, respectively.

Table 1. Modeled water levels, interpreted as events and return period for existing and future conditions

Modeled Water Level (ft NAVD)	Event (return period)		
	Existing conditions	+1 ft SLR (2050)	+3 ft SLR (2100)
6	MHHW (two days)	MLHW (one day)	MSL (12 hours)
7	Spring tide (two weeks)	MHHW (two days)	-
8	50% annual chance (two years)	Spring tide (two weeks)	MLHW (one day)
9	1% annual chance (one century)	50% annual chance (two years)	MHHW (two days)
10	-	1% annual chance	Spring tide

[3] Data from Lacy and Hoover (2011) describe waves that attenuated before reaching the internal marsh station, so the precise rates of wave attenuation could not be measured. Data from Brand et al. 2010 (wave attenuation in south San Francisco Bay) was across shallow subtidal shoals, not marshes, and as such is not applicable to this exercise.
[4] Station ID: 9414290
[5] Station ID: 9414863
[6] Table 5.3 p. 117

		(one century)	(two weeks)
11	-	-	50% annual chance (two years)

2.2.2 Wave Height

Estimates and observations of significant wave height in the Bay suggest that typical 1% significant wave height ranges from 2 ft to 4 ft for most of the Bay's marshes (DHI 2011, Lacy and Hoover 2011, see also wind data from the Richmond Bridge, NOAA, 2012). Sites subject to local sheltering, such as Corte Madera Bay, experience waves in the lower portion of this range. Areas just inside Golden Gate, which are exposed to larger ocean swell, and portions of the South Bay with the longest fetches, experience waves at or above the high end of this range. The actual extreme wave heights depend on local bathymetry, wind speed, wind direction, and fetch. Observations at Corte Madera Bay (Lacy and Hoover, 2011) indicate that the mudflat significantly attenuates waves before they reach the marsh. Since there are no long term wind and wave records at Corte Madera Bay, a generalized set of wind and resulting wave conditions was derived from empirical methods for estimating the relationship between wind speed and wave height (USACE, 2002). For these estimates, the assumed water depth was 8 ft, the assumed fetch was 10 miles, and the wind speeds were selected based on long term observations at San Francisco International Airport. The nominal wind speeds and wave heights selected for WHAFIS modeling, along with the nominal wave periods, are summarized in Table 2.

Table 2. Wind speed and estimated wave height and period (USACE, 2002)

Wind Speed	Nominal wave height	Wave period
10 mph	1 ft	2.1 s
20 mph	2 ft	2.5 s
30 mph	3 ft	2.9 s

Note that since both water levels and wind waves are random processes that are only partially correlated, the likelihood of both occurring with extreme conditions is less than the likelihood of them happening individually. For example, the likelihood that both water levels and waves occur simultaneously at their individual 10% annual chance magnitude is less than the 10% annual chance. This reduced likelihood of simultaneous events occurred during the USGS's two-month field deployment: the peak observed water level, approximately 8 ft NAVD, was also the annual peak for the winter of 2009-2010. However, wave heights during this event were less than a foot at the offshore station and even smaller closer to shore.

2.2.3 Vegetation

The vegetation modeled in the WHAFIS profile represents typical vegetation in North Muzzi Marsh, which fringes the west side of Corte Madera Bay (BCDC and ESA

PWA, 2013; Figure 1-5). The profile includes a broad plain of pickleweed (*Sarcocornia pacifica*) on top of a steep scarp (Figure 1). At the outboard edge of the marsh, where a historic remnant levee has been removed from modeling the geometry (see next section), the assigned vegetation is a band of native Pacific cordgrass (*Spartina foliosa*) along the lower elevations, as is found at Muzzi Marsh. Pickleweed occupies the higher zones on the marsh. Cordgrass grows as a tall, straight emergent plant, and typically has a stem diameter of about half an inch, a height of about 2.5 to 4.5 feet, and a density of approximately 6 stems per square foot (NHC 2011). Pickleweed has a smaller shrub-like structure, forming a dense mat with many branching stems lying prostrate. Pickleweed stems are about an eighth of an inch in diameter, and the plant grows to a maximum of 2 ft tall (NHC 2011). Within the WHAFIS profile, the cordgrass-dominated area converts to pickleweed at MHHW, which is modeled at 120 ft inland from the edge of the scarp. Similar vegetation distribution patterns can be seen in both Heerdt and Muzzi marshes. Table 3 from NHC (2011) documents WHAFIS marsh vegetation parameters used in this study.

Table 3. Proposed WHAFIS vegetation parameters from NHC (2011)

Scientific Name	Common Name	Effective drag coefficient	Unflexed stem height (ft)	# plants per sq. ft.	Base stem diam. (in)	Mid stem diam. (in)	Top stem diam. (in)	Front area ratio
Spartina foliosa	Pacific cordgrass	0.1	3.5	6	0.5	0.5	0.5	1.59
Sarcocornia pacifica	Pickleweed	0.1	2	28	0.4	0.4	0.125	0.1

2.2.4 Geometry

The modeled WHAFIS profile geometry is displayed in Figure 1. This profile displays idealized bed elevations from the seamless USGS topographic/bathymetric data set measured and compiled by Foxgrover et al. (2011). To represent typical conditions along the Corte Madera shoreline, we chose a profile that did not include an outboard levee. Since WHAFIS does not consider the effects of friction over bare sediment (e.g., unvegetated mudflats are not modeled to have an effect on waves, contrary to field observations – see “Results” below), the profile domain begins just offshore of the marsh.

It is important to note that the shallow topographic data was collected using airborne LiDAR, which can result in an offset due to the LiDAR reading the elevation of the top of vegetation instead of the ground surface. At Corte Madera Bay, the offset was observed to be approximately 23 cm, or 9 inches (Athearn et al. 2010, Foxgrover et al. 2011). However, this offset likely varies with vegetation species, density, and other factors.

3 Results

Wave modeling was conducted to expand upon the wave observations collected in Corte Madera Bay (Lacy and Hoover, 2011). The wave modeling provides a broader perspective of conditions at the site by simulating wave attenuation over the marsh plain and forcing conditions not observed during the field measurements. This perspective helps describe the wave attenuation ecosystem services provided by the mudflat and marsh.

No local data are available for calibrating the WHAFIS model. Although the USGS deployed wave gages offshore and within the Corte Madera Bay marsh, at no time during the study period was significant wave energy observed at the wave gage located within the marsh (Lacy and Hoover 2011). Thus, the only observational insight about wave attenuation over the marsh is that for conditions during the 2010 deployment, waves were completely attenuated somewhere between the marsh edge and the gage within the marsh. The attenuation rate cannot be determined from the available data. The USGS study also found that, contrary to the assumptions of the WHAFIS model, mudflats within Corte Madera Bay attenuated waves by as much as 80% (Lacy and Hoover, 2011). In the absence of calibration data on the marsh, the marsh vegetation parameters can only be selected based on other sources, e.g. FEMA (1988) and NHC (2011). In addition, the model's sensitivity to those parameters can be evaluated by changing the spatial distribution of different types of vegetation across the profile, and examining resulting effects on wave attenuation, as described in Section 3.3 below.

3.1 Water Level

Since water levels set water depths, and in shallow water wave height is largely controlled by the depth of the basin over which the wave is propagating, water level is the largest determinant of wave height. As a result, waves over marshes are largely depth-limited. This is most dramatically illustrated at the marsh scarp, where wave heights decrease significantly by wave-breaking as waves pass over the scarp. This sudden decrease in wave height focuses wave energy on the scarp itself, and leads to active erosion that maintains the steep face of the scarp. As water levels increase, the rapid attenuation of wave energy over the scarp decreases. At a higher water level, the same size incident wave at the marsh edge yields larger wave heights within the marsh, less dissipation due to bed friction, and increased wave energy within the marsh plain.

These phenomena are illustrated in the WHAFIS model results presented in Figure 2. This figure displays WHAFIS results for 2-ft wave crests at two base water levels: 7 ft NAVD (about a foot above the marsh ground surface), and 9 ft NAVD (about 3 ft above the marsh). Water levels in Corte Madera Bay reach 7 ft NAVD during high tides over a few days approximately once every two weeks. At this water level, waves break at the scarp, resulting in a dramatic decrease in the wave energy that is available to penetrate into the marsh interior. In the first 160 ft of marsh plain, where the bed transitions from mudflat to the marsh plain elevation, depth-limited breaking causes a two-foot wave to decrease by more than 70%.

However, for the 9-ft case (roughly equivalent to a 100-year water level, or 1% annual event), increased water levels result in relatively less wave dampening over the same distance. Since a two-foot wave at this water level is less than the depth-limited wave height, wave attenuation over the marsh plain is dominated by frictional dissipation caused by vegetation. Over the same 160 ft distance considered in the 7-ft case described above, a two-foot wave experienced only 17% reduction in height. In addition, once the wave entered the marsh plain, it attenuated at a slower rate than the wave at 7-ft. For instance, while in the 7-ft case, the wave attenuates by more than 60% over the next 500 feet of marsh, in the 9-ft case, the wave only attenuates by slightly less than 40% over the same distance. When the water level is higher, waves experience less attenuation because they are further from the vegetation, and therefore subject to less dissipation.

Modeled scenarios also included two-foot waves with water levels at 6 and 8 ft NAVD (Figure 2), but these scenarios are not shown on a figure. For the 6 ft case, only the outer edge of the marsh was inundated by the wave, and the wave completely broke and dissipated at the scarp without entering the marsh plain. This is the expected result for a wave whose base water level is roughly equivalent to the elevation of the marsh plain. At a base water level of 8 ft, the wave experiences relatively less attenuation from depth-limited breaking than the 7 ft scenario, and accordingly describes an intermediate result between the 7 ft and 9 ft scenarios.

In addition to considering water levels likely under present sea level conditions, the WHAFIS model was used to evaluate wave conditions on potential future scenarios which include SLR. Model results for two-foot waves with 11-ft NAVD water levels are shown in Figure 2. The 9-ft water level is shown as a reference point for the upper end of present day extreme conditions, on the order of the 1% annual event as described above. The 11-ft water level represents the 1% annual event with two feet of SLR. Like the 9-ft scenario, waves in the 11-ft scenario are not depth limited, and attenuation is controlled by the friction from vegetation. For the 11-ft scenario, the considerable depth between the base water level and the marsh surface results in wave attenuation of only half a foot over the entire marsh plain.

3.2 Wave Height

The WHAFIS model was also used to assess the influence of wave height on wave attenuation across the marsh plain. Figure 3 displays wave attenuation for 1-foot, 2-foot, and 3-foot waves at a water level of 9 ft NAVD. Waves were modeled at this water level to minimize the effects of depth limitation and isolate the effects of friction over a range of plausible storm event scenarios. For the 9-ft water level shown in Figure 3, only the 3-ft wave is depth limited over the marsh plain. When the 3-foot wave reaches the scarp, it experiences rapid attenuation, and is dissipated to almost the same height as the 2-foot wave. Since the 1-foot wave is smaller than the 2-foot wave and has correspondingly lower wave-induced currents, the 1-ft wave is subject to relatively less vegetation friction than the 2-ft wave, and as such attenuates at a lower rate over the marsh plain. Towards the back of the marsh at the end of the transect, all three wave crest values converge to within approximately 0.5 feet of each other. This convergence is centered around an elevation that balances the wave energy dissipation due to the vegetation, and energy input from the ambient wave field.

3.3 Vegetation

The WHAFIS model was used to test the sensitivity of wave attenuation to vegetation parameters by modifying the extent of cover by different plant species. The starting point for this sensitivity analysis was typical conditions, which consist of cordgrass occupying the outboard 120 ft of the marsh due to lower elevations, and pickleweed occupying the remainder of the marsh. The alternate conditions were modeled were:

- All cordgrass – Change pickleweed on inboard section of marsh to cordgrass. This condition would is representative of a downshift in the vegetation from a middle marsh community to a low marsh community in response to rising sea levels that out-pace sediment accretion.
- All pickleweed – Change cordgrass on outboard edge of marsh to pickleweed. This condition is representative of an eroding fringing marsh.
- No vegetation – Remove all vegetation from the marsh plain. This condition is representative of a drowned tidal marsh that has converted to an unvegetated mudflat in response to rising sea levels that significantly out-pace sediment accretion.

As shown in Figure 4, the predicted difference between species of vegetation is negligible for a water level of 9 ft NAVD (top panel) and very small for a water level of 7 ft NAVD (bottom panel). Wave attenuation is less sensitive to vegetation at the higher water level because the waves are elevated further from the friction losses due to marsh vegetation, and therefore less sensitive to vegetation dissipation in general. Close examination of the 7-ft wave profile indicates that cordgrass attenuates waves slightly more than pickleweed when these species are parameterized according to values from NHC (2011). The wave profiles without vegetation show the largest change from typical conditions. However, because WHAFIS does not consider any dissipation to occur over bare sediment beds, the wave heights for this scenario are over-predicted. As evidenced by Lacy and Hoover (2011), the muddy bottom at Corte Madera Bay causes significant wave attenuation through bottom frictional dissipation.

3.4 Geometry

In terms of affecting water depths, changes in marsh plain elevation due to accretion or erosion of the mudflat are identical to changes in water level, so they are not modeled as a different case. For example, waves propagating across an 8-ft NAVD water level over the existing 6-ft marsh plain would be equivalent to waves propagating on a 9-ft NAVD water level over the marsh plain that had accreted by one foot (to 7 ft NAVD).

In order to examine the effect of the outer scarp on wave attenuation, the model geometry was modified such that the conversion from marsh plain to mudflat was a gentle slope instead of a sudden steep scarp. Because WHAFIS does not consider attenuation due to bed friction over mudflats, this change in geometry has a limited impact. For a higher water level of 9 ft (Figure 5, top panel), the change to a sloping mudflat has no effect on wave heights. For the 7-ft water level (Figure 5, bottom panel), the sloping mudflat causes depth-limited breaking to occur over the mudflat. As the water over the mudflat becomes shallower, waves demonstrate a corresponding decrease in height. However, since this same process sets wave heights at the beginning of the marsh plain, there is no difference in predicted wave height over the marsh plain. In other words, the waves break gradually over the sloping mudflat, or suddenly at the scarp, but in both cases, depth limitation dictates that the ultimate wave height at the beginning of the marsh plain under both scenarios will be the same. It is important to recognize that this does not necessarily mean that the erosive power of the wave breaking over the mudflat and the wave breaking at the scarp are the same. The breaking and sudden deceleration of waves at the scarp exposes the scarp to a considerable amount of erosive energy, more than if the wave was gradually depth-limited over a gradual slope. For these reasons, wave height is an imperfect surrogate for erosive wave energy, which should be considered when applying the WHAFIS results to expectations for the performance of natural systems.

After the initial and sometimes abrupt breaking that occurs at the marsh edge, the remainder of the wave attenuation occurs gradually through vegetative frictional losses over the marsh plain. As such, the marsh width determines the wave height. To highlight the role of marsh width, the predicted wave height transects from previously described runs (Section 3.1) are displayed as the relative attenuation of waves as a function of marsh width (Figure 6). The relative attenuation is shown by scaling the wave height across the marsh by its incident height immediately before encountering the marsh edge.

For those water levels which result in depth-limited waves, the first part of these curves typically show the steepest decrease. For example, this steep decrease is readily apparent for the 2-ft wave traveling across 7-ft and 8-ft water levels (Figure 6a) and for the 3-ft wave traveling across 7-ft, 8-ft, and 9-ft water levels (Figure 6b). Note that for the same water level, the 3-ft wave experiences more rapid attenuation than the 2-ft wave as a function of incident wave height (wave height immediately before encountering the marsh edge). This occurs because the larger waves are influenced by the vegetated bed more strongly, and therefore see larger reduction in size for the same marsh width. However, since the 3-ft wave had a larger incident wave height, its absolute size stays larger. But due to the faster attenuation, the two wave heights converge to similar heights after approximately 1,000 ft of marsh (Figure 3).

The impact of marsh width on wave attenuation may be considered from a management perspective, to inform target marsh size. While even a relatively narrow strip of marsh can perform significant wave height reduction via depth limited breaking at less extreme high water conditions, a wider marsh provides additional attenuation, particularly for the higher extreme water levels when flooding is worse. As an example, a 1-ft wave height was selected as a threshold small enough to be considered less than significant. Waves below this threshold height do not affect FEMA flood mapping since they are smaller than the differential in FEMA freeboard specifications for assessments with waves (1 ft freeboard) and without waves (2 ft freeboard).

For the 2-ft and 3-ft incident wave heights shown in Figure 6, the minimum marsh widths to reduce the incident wave to a 1-ft wave are summarized in Table 4. The minimum marsh width is more sensitive to water level than wave height, and increases nonlinearly with water level. This is consistent with wave attenuation being dominated by depth limitation for lower water levels, and by vegetation dissipation for higher water levels. Note that the amount that extreme water level exceeds high marsh elevation is relatively constant around the Bay since the high marsh plain is typically at an elevation of MHHW and the 1% annual chance water levels are about three feet above MHHW. If the WHAFIS model accurately represents wave attenuation, then a thousand feet is an order of magnitude estimate for minimum width of healthy marsh to attenuate waves to below 1 foot in height. If the bed elevation relative to extreme water levels is lower, for instance, in the case that marshes cannot accrete sediment fast enough to keep pace with SLR, then the marsh width would need to be greater to accomplish the same reduction in wave height.

Table 4. Minimum marsh width, in feet, to reduce incident wave to a 1-ft wave.

	Water level (ft NAVD)		
Incident wave height (ft)	**7**	**8**	**9**
2	40	300	840
3	50	320	980

3.5 Interactive Visualization Tool

The full set of model scenarios executed for this study can be accessed through the accompanying interactive visualization tool. This tool allows users to explore a greater range of model scenarios than just those presented as static figures in this report. Using this tool, the user can select model scenarios which may be applicable to particular a stretch of Bay shoreline or can visualize scenarios with different wave parameters.

This tool is a Microsoft Excel file, 'WHAFIS_wave_vis.xls', which contains all the model output aggregated into a single interactive figure. The figure is formatted similarly to the static figures which are included with this report. In all instances, the figure shows the characteristic mudflat and marsh bathymetry profile used as WHAFIS input. Then, in a panel to the right of the figure, the user can select several options to control the WHAFIS output in the figure. Options include:

- **Type of Plot** – Select which wave parameter is plotted from among the wave crest elevation, wave height, or percent reduction relative to the incident wave height.
- **Bed Profile** – Select the shape of the bed with either a steep scarp or a gentler slope in front of the marsh.
- **Vegetation** – Select from the existing vegetation (cordgrass (CG) in front of pickleweed (PW)), all pickleweed, all cordgrass, or no vegetation.
- **Offshore Wave Height** – Select from an offshore wave height of 1 ft, 2 ft, or 3 ft.

After selecting from among these options, the user can also decide which water levels to display. Note that not all possible combinations are available from the list of options. For instance, when selecting one option, such as all pickleweed vegetation, other options, such as the slope bed profile, may not be available. The figure updates with the selected run scenarios when the 'Plot' button is clicked on with the mouse cursor. The figure is formatted for printing if selected scenarios are to be shared.

In order to be interactive, the tool uses macros, which may not be enabled by default in the user's Excel environment. In the event that the macros produce an error that disrupts the tool's function, closing the file (without saving) and re-opening the file should correct the issue. A user should consult the Excel help for more information macros, including how to enable them.

3.6 Comparison with SWAN

The two-dimensional wave model, Simulating WAves Nearshore (SWAN), predicts the generation, dissipation, propagation, and breaking of wind waves (Delft University of Technology, 2012). By considering these processes, the model can represent the factors which determine the wave field in Corte Madera Bay. The SWAN model was configured to represent Corte Madera Bay using bathymetry and topographic data collected and assembled by the USGS (Foxgrover et al., 2011). The model was calibrated and validated to the 2010 USGS wave data collected over mudflat and generally demonstrated good agreement between model predictions and observed wave heights. Additional details about the SWAN model setup, calibration, and validation can be found in van der Wegen and Jaffe (2012).

The model configurations used for WHAFIS and SWAN were different. As shown in Figure 7, the two models used different interpretations of the bed elevation data set: a simplified profile was selected for WHAFIS whereas SWAN preserved marsh plain micro-topography. Some of the SWAN vegetation parameters differed from the WHAFIS parameters described above in Section 2.2.3. The SWAN model assumed the entire transect was populated with cordgrass, whereas the WHAFIS model assumed cordgrass populated only the front edge of the marsh and pickleweed populated the remainder of the marsh plain. Based on the minimal sensitivity of WHAFIS results to vegetation type (Section 3.3), this difference in vegetation configuration is not likely to be a significant contributor to differences in model output. In addition, the two models had different guidance on the vegetative drag coefficient; whereas the WHAFIS literature recommends 0.1 (FEMA, 1988), the SWAN literature recommends 0.5 (van der Wegen and Jaffe, 2012). Because of different model domains and since SWAN attenuates waves over the mudflat whereas WHAFIS does not, the wave heights incident to the marsh were different. For example, the SWAN incident wave heights varied with water level from 2.5 to 3 feet while the WHAFIS incident wave heights were fixed at 3 ft.

To facilitate comparison between these different configurations, the modeled wave heights are scaled by the incident wave height in Figure 7. Despite these differences, the models exhibit similar characteristics in the predicted wave attenuation. Both models predict rapid attenuation over the scarp edge as a result of reduced wave heights due to wave breaking. The predicted attenuation due to breaking is most similar in the first hundred feet of marsh for the 7-ft water level when breaking is more dominant. For the higher water levels, WHAFIS does not predict as rapid attenuation as SWAN in the next several hundred feet landward of the scarp. This dissimilarity is likely due to differences between the models in how vegetation parameters relate to wave dissipation. After traveling over the marsh for approximately 500 ft, the differences between the results from the two models decrease as the predicted wave heights converge toward asymptotic values that are a function of water level.

4 Conclusions and Recommendations

This section describes our conclusions and recommendations for further planning, research, and implementation.

4.1 Conclusions

The conclusions of the WHAFIS modeling are summarized below.

4.1.1 Mudflat and Marsh Roles in Wave Attenuation and Sea Level Rise Vulnerability

Overall, both mudflats and marsh plains within Corte Madera Bay attenuate waves, and play a significant role in protecting the Corte Madera shoreline from wave damage. However, the mechanisms by which the two habitats attenuate waves differ: mudflats attenuate waves primarily through bottom frictional dissipation, while tidal marshes attenuate waves through both depth limitation and vegetation-induced friction. The WHAFIS model does not include the effects of dissipation over the mudflat, it is useful for describing how vegetative dissipation operates over marshes. Note that although WHAFIS does not explicitly account for energy loss due to the muddy sediment underneath the vegetation, and the characteristics of the sediment may also affect wave attenuation. Other studies comparing wave dissipation rates between mudflats and vegetated marsh have found marsh to be at least one half more dissipative and up to ten times more dissipative (Anderson et al., 2011), so WHAFIS does account for the dominant source of wave energy loss.

As waves travel across Corte Madera Bay towards the shoreline, they encounter a broad swath of subtidal and intertidal mudflats. Based on data from Lacy and Hoover (2011), Corte Madera Bay mudflats are capable of attenuating waves by up to 80%. Additional USGS data at other San Francisco Bay sites suggests attenuation by mudflats is significant for other Bay shorelines. However, it is likely that the combined effects of sea level rise and decreasing suspended sediment supplies will negatively impact the future ability of Corte Madera Bay mudflats to attenuate waves. Recent research indicates that mudflat elevations in the vicinity of Corte Madera Bay have likely decreased since the mid 19th century, except during the 1895 to 1947 time period when mudflats prograded beyond 1855 conditions, possibly related to sediment pulses associated with hydraulic mining or urban and agricultural development in the Central Valley (Foxgrover et al. 2011). Decreasing mudflat elevations suggest decreasing sediment supply to Corte Madera Bay either from the Bay and/or the Corte Madera Creek watershed. This is consistent with additional recent research that demonstrates a likely sediment deficit in the Bay since 1999 (Schoellhamer, 2011). As a result, Corte Madera Bay mudflats may not be able to keep pace with SLR, resulting in a decreasing ability over time to attenuate waves as water levels rise and water depths above the mudflats increase.

As waves approach the marsh plain from the mudflats, the rate at which they attenuate is inversely proportional to the steepness of the transition between the mudflat and the marsh. Sloping transitions lead to gradual attenuation, while steep scarps lead to sudden attenuation. Regardless of the type of transition, however, once the waves enter the marsh plain, they are subject to additional attenuation. Under existing conditions, since water depths over the marsh are unlikely to exceed much more than 3 ft during the 1% annual chance event, and since the breaking depth for shallow water waves is approximately 78% of the water depth (FEMA, 1988), the peak potential wave height just after waves cross onto the marsh plain is approximately 2.5 ft. As the wave travels across the marsh plain, frictional losses from vegetation further attenuate wave heights. Rates of wave attenuation across the marsh plain decrease as water levels rise, because the waves are further from the dissipative forces of the marsh vegetation. However, at a given water level, the rates at which waves attenuate increase with wave height, because larger waves cause stronger currents deeper into the water column, thereby experiencing greater drag forces (and energy loss) when these currents interact with marsh vegetation.

The type and structure of vegetation within a marsh likely affects its surface roughness and therefore its ability to dissipate wave energy. Using the parameters described in NHC (2011), it appears that cordgrass can potentially attenuate waves slightly more than pickleweed. Further research into this question is necessary to examine if this is an artifact of the parameters or an actual physical phenomenon. Future research and modeling should also consider the potential for marsh plain vegetation communities to change as sea levels rise and inundation regimes change – e.g., reducing the rigor of pickleweed plants (Woo and Takekawa, 2012), or converting from high marsh pickleweed plains to lower marsh cordgrass communities. Such vegetation changes could impact wave attenuation across the marsh plain.

4.1.2 Wave Attenuation, Marsh Loss, and Adaptation Strategies

One of the primary conclusions from the WHAFIS modeling is that a loss of mudflats and marshes from a combination of rising sea levels and decreased suspended sediment concentrations could impact the flood risk along the Corte Madera shoreline. Decreases in the extent and/or elevation of mudflats and marshes would result in a reduction of wave attenuation, potentially leading to higher wave run-up and overtopping at the land margin. Therefore, management strategies to reduce flood risk should focus on maintaining robust mudflats and marshes as landscape features.

It is doubtful that current trends in sea level rise acceleration and suspended sediment concentrations will facilitate the large-scale expansion of marshes and mudflats within Corte Madera Bay and other portions of the Central Bay. Therefore, management strategies should focus on maintaining the mudflats and marshes that currently exist, and helping them keep pace with sea level rise. Strategies to preserve the mudflat width and elevation will maintain the bed friction and depth limitation necessary for wave attenuation. Similarly, preservation of the marsh scarp (preventing its retreat relative to the shoreline) will help ensure that waves break far from the shoreline. Managed retreat and/or the construction of broad, gradually sloping wetland-upland edge areas are examples of strategies that could do both by allowing marsh habitats to gradually transgress over upland habitats as lower marsh areas convert to mudflat. The installation of coarse beaches or breakwaters offshore could also help to prevent or minimize scarp erosion. Other promising avenues for proactive mudflat/marsh maintenance are strategies that support the capacity of the marsh plain to accrete and sustain its elevation relative to rising sea levels. Such strategies could include careful, selective application of sediment to marshes to facilitate accretion, enhanced sediment trapping on the marsh plain, efforts to improve tidal circulation (and thus suspended sediment deposition) in areas where it is limited, or projects to enhance the density and health of vegetation communities on the marsh plain. These management measures and adaptation strategies are described in additional detail in (BCDC and ESA PWA, 2013).

4.1.3 Model Skill and Uncertainty

Like most models, the WHAFIS model is only as good as (1) the assumptions utilized in its construction, and (2) the data that are input into the model. The model could be refined if the following limitations were addressed:

1. Water levels and wave conditions during the observation period in January-March 2010 provide only a limited perspective of wave attenuation over the vegetated marsh. Even during the largest events of the observation period, wave energy that reached the bayward edge of the marsh was attenuated to negligible values at the marsh observation station within the marsh plain (Lacy and Hoover 2011). Therefore, observations were not sufficient to characterize the attenuation rate, or define a minimum lower limit of the rate that would achieve negligible wave energy in the marsh interior.

2. Observations indicated that the mudflat attenuates waves, but in ways that are not readily captured by simple wave dissipation calculations. These calculations could provide initial estimates to inform planning, but more sophisticated models, such as SWAN, are recommended for providing design criteria.

3. Although WHAFIS and SWAN exhibit some differences in predicted wave attenuation in the first few hundred feet of marsh plain, their predictions converge further into the marsh. This agreement indicates that when assessing marsh's role in wave attenuation, the freely-available and simpler, 1D WHAFIS is sufficient. However, to incorporate effects of Bay-scale wave generation and propagation, as well as attenuation over mudflats, a two-dimensional model such as SWAN is recommended.

4.2 Recommendations

The modeling results and suggestions presented in this report are primarily applicable to wave attenuation within Corte Madera Bay. We recommend the following project elements to improve the overall understanding of wave attenuation across different Bay marshes, and how mudflats and marshes may be utilized as elements of a comprehensive coastal flood management program:

1. **New data collection.** The collection of additional wave attenuation data in marshes throughout the San Francisco Bay (including San Pablo Bay and the

South Bay) will help scientists, engineers, and planners understand regional variability in wave attenuation, and the physical and ecological factors that contribute to how and under what conditions mudflats and marshes attenuate wave energy.

2. **Coordination with FEMA on flood mapping procedures for the Bay shoreline.** Currently, FEMA flood maps are being updated to consider the influence of mudflats and marshes on wave attenuation and concurrent flood risk. This consideration of wave attenuation in FEMA flood mapping procedures will result in more accurate maps that incentivize the protection and enhancement of mudflats and tidal marshes.

3. **Analyze alternative areas of the Bay shoreline.** Together with the field data collection activities described in (1), wave modeling efforts for other Bay shoreline areas could help improve the accuracy of the parameters that serve as inputs to the WHAFIS model, and help identify areas where excessive wave runup due to lack of mudflats/marshes increases the flood risk. Excellent candidates for modeling include shorelines near Hayward, East Palo Alto, and Richmond. All of these areas have varying degrees of existing outboard marsh and mudflats that could provide additional opportunities to calibrate and apply the WHAFIS model.

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6 Glossary

Bottom frictional dissipation. Friciton between the water moving under a wave and the sediment at the bottom of the water column, which serves to dissipate kinetic energy within the wave, reducing its height.

Depth-limitation: The process by which waves attenuate due to the height of the wave being larger than the depth of the water over which the wave is propagating. In shallow water, waves break when their wave height H is larger than 0.8 times the water depth h, or when $H > 0.78\ h$ (FEMA, 1988).

Incident wave height. The height of a wave just before it propagates over a surface such as a marsh plain. See Figure 1.

Vegetation-induced friction. Friction between the water moving under a wave and the stationary vegetation on the marsh plain, which serves to dissipate kinetic energy within the wave, reducing its height.

Wave attenuation: The process by which waves heights decrease as they travel across substrates such as mudflats or tidal marshes. In the WHAFIS model, waves attenuate either through depth limitation or vegetation-induced friction.

Wave crest elevation. The distance between the highest point of the water surface deflected by a wave and some arbitrary elevation datum. In this report, the North American Vertical Datum (NAVD) is used as the reference datum. See Figure 1.

Wave height. The distance between the highest and lowest points on the water surface when it is deflected by wave motion. See Figure 1.

7 Figures

Figure 1. Representative Marsh Cross Section

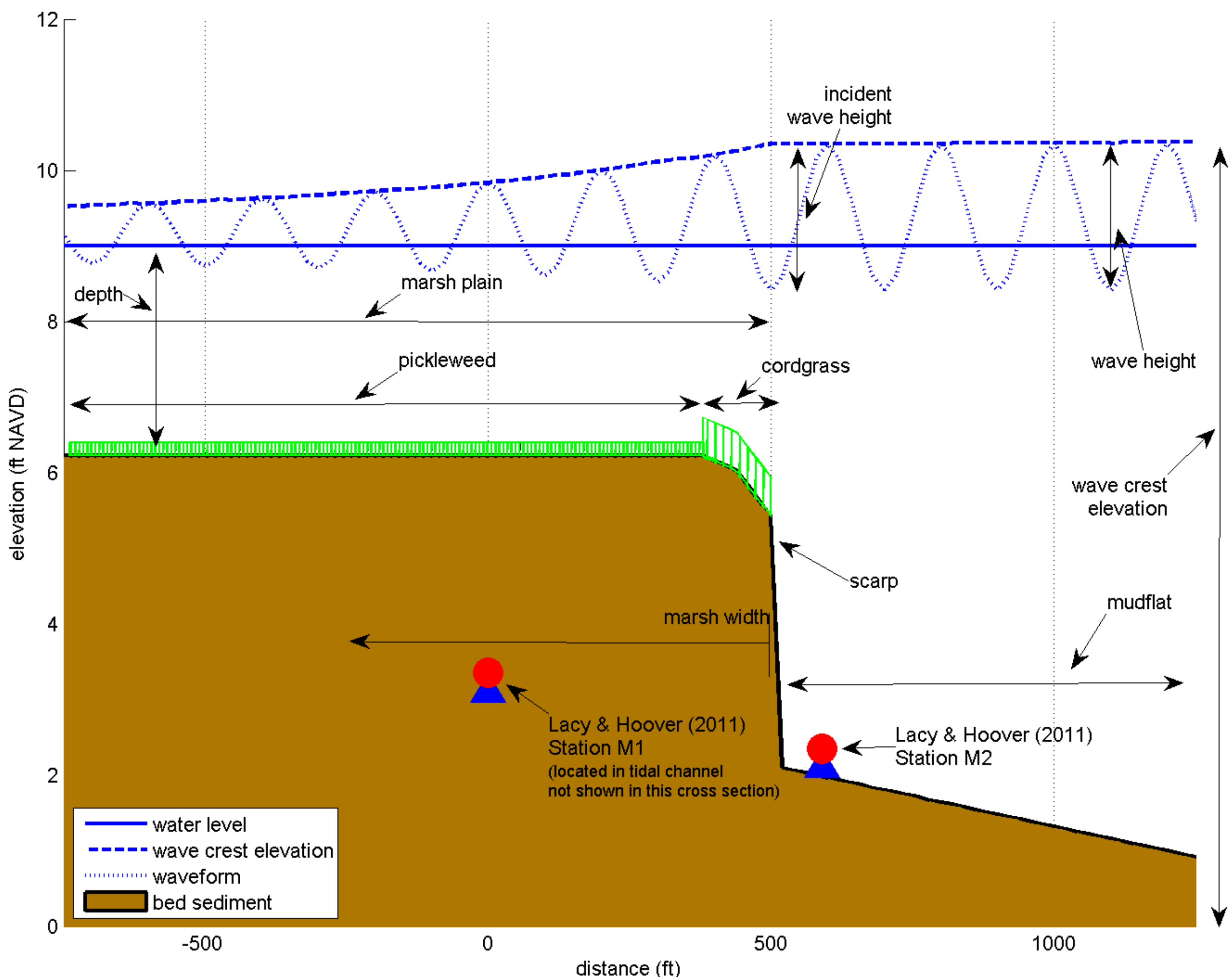


Figure 2. WHAFIS-predicted wave attenuation over marsh plain for water level of 7 ft, 9 ft, and 11 ft NAVD, wave height of 2 ft.

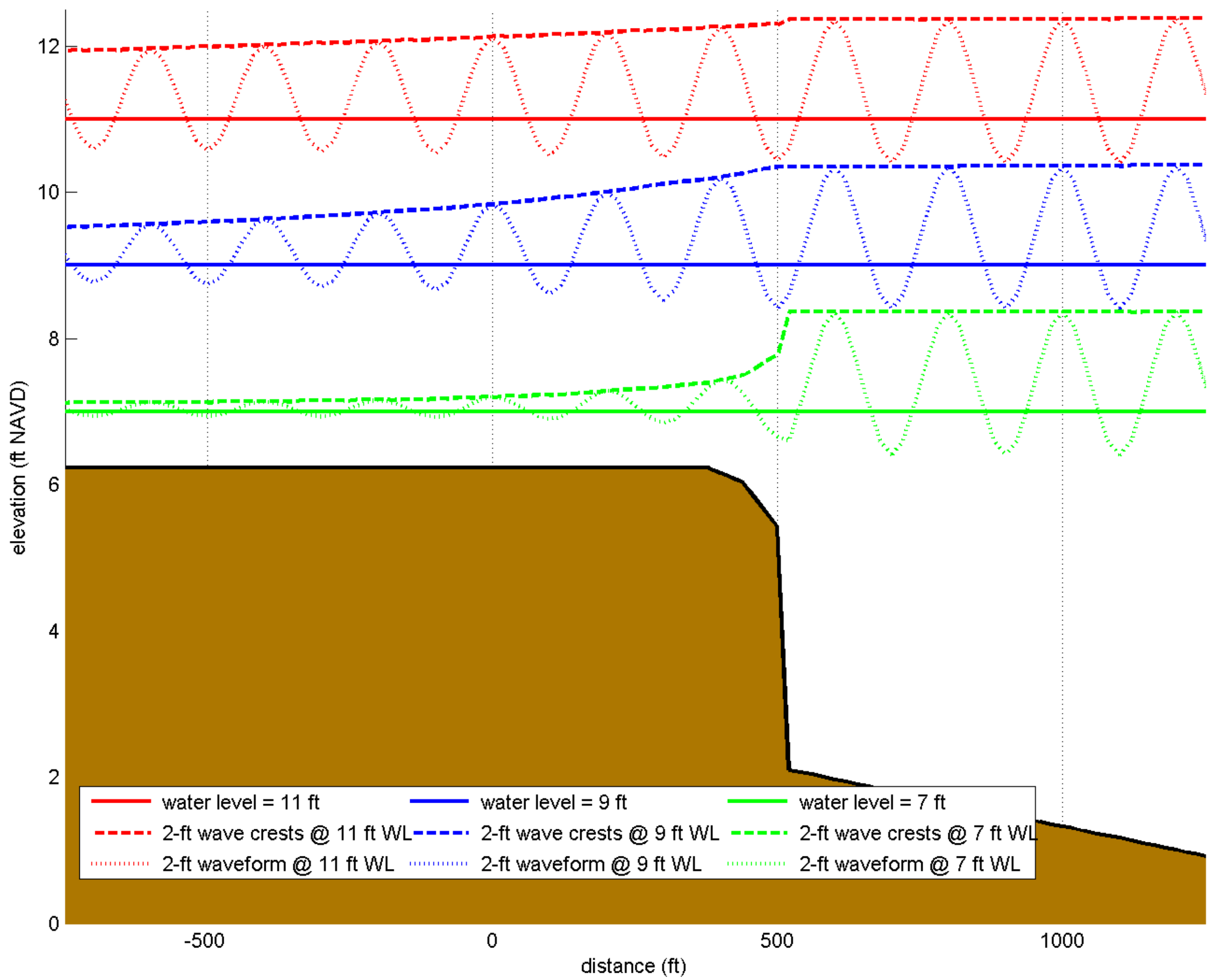


Figure 3. WHAFIS-predicted wave attenuation over marsh plain for water level of 9 ft NAVD, wave heights of 1, 2, and 3 ft.

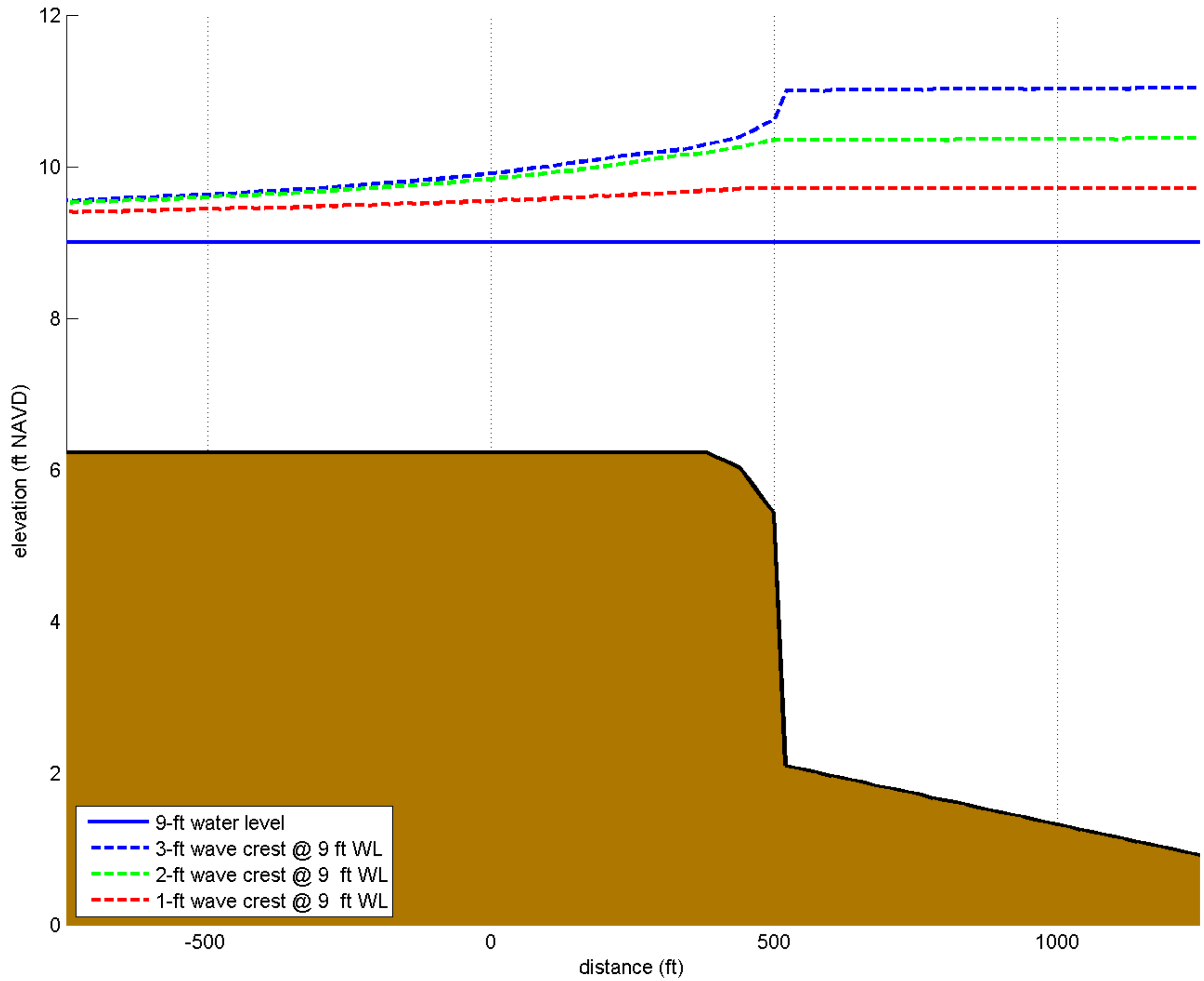
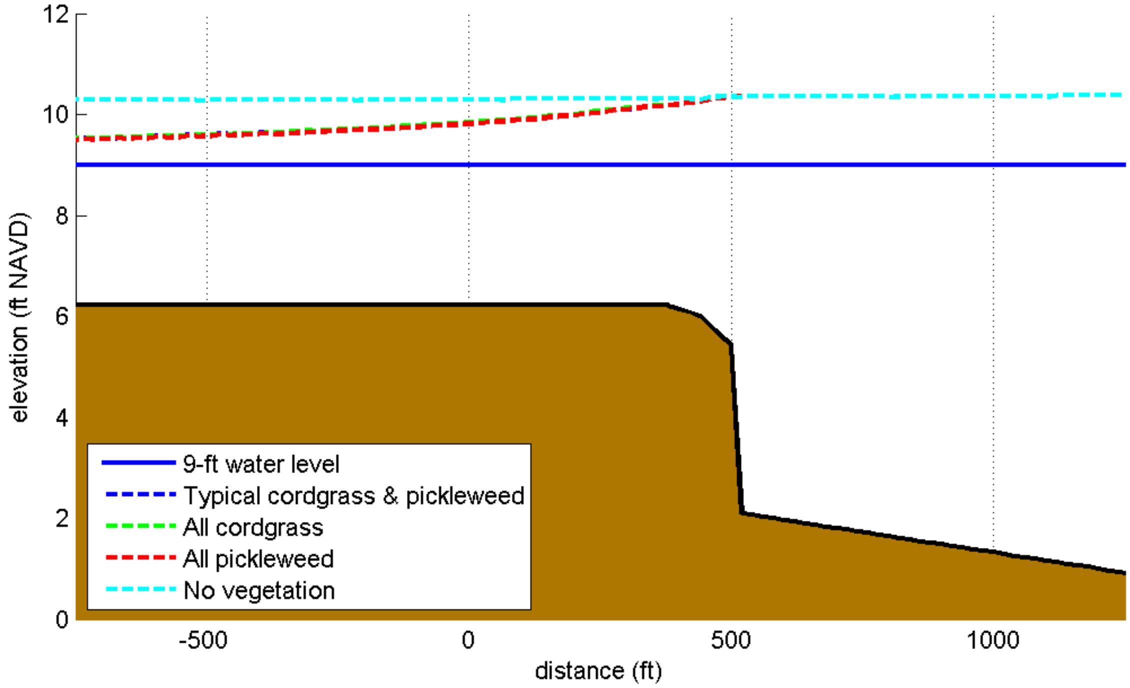
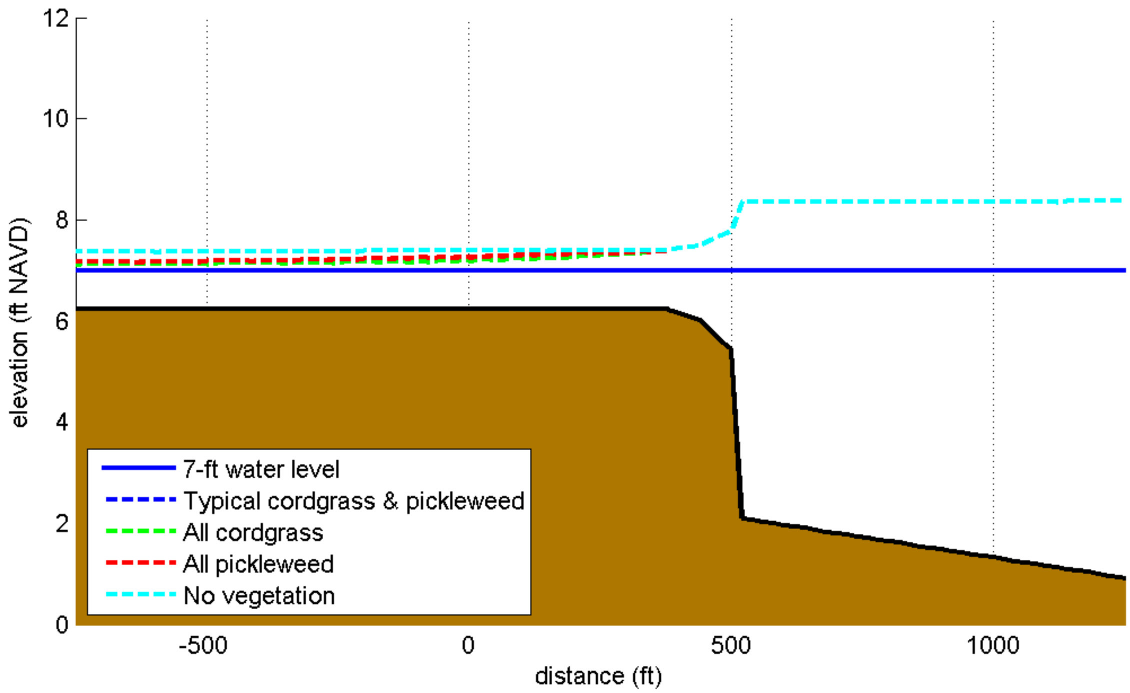


Figure 4. WHAFIS-predicted wave crest elevation sensitivity to vegetation for water level of 9 ft NAVD (top panel) and 7 ft NAVD (bottom panel).





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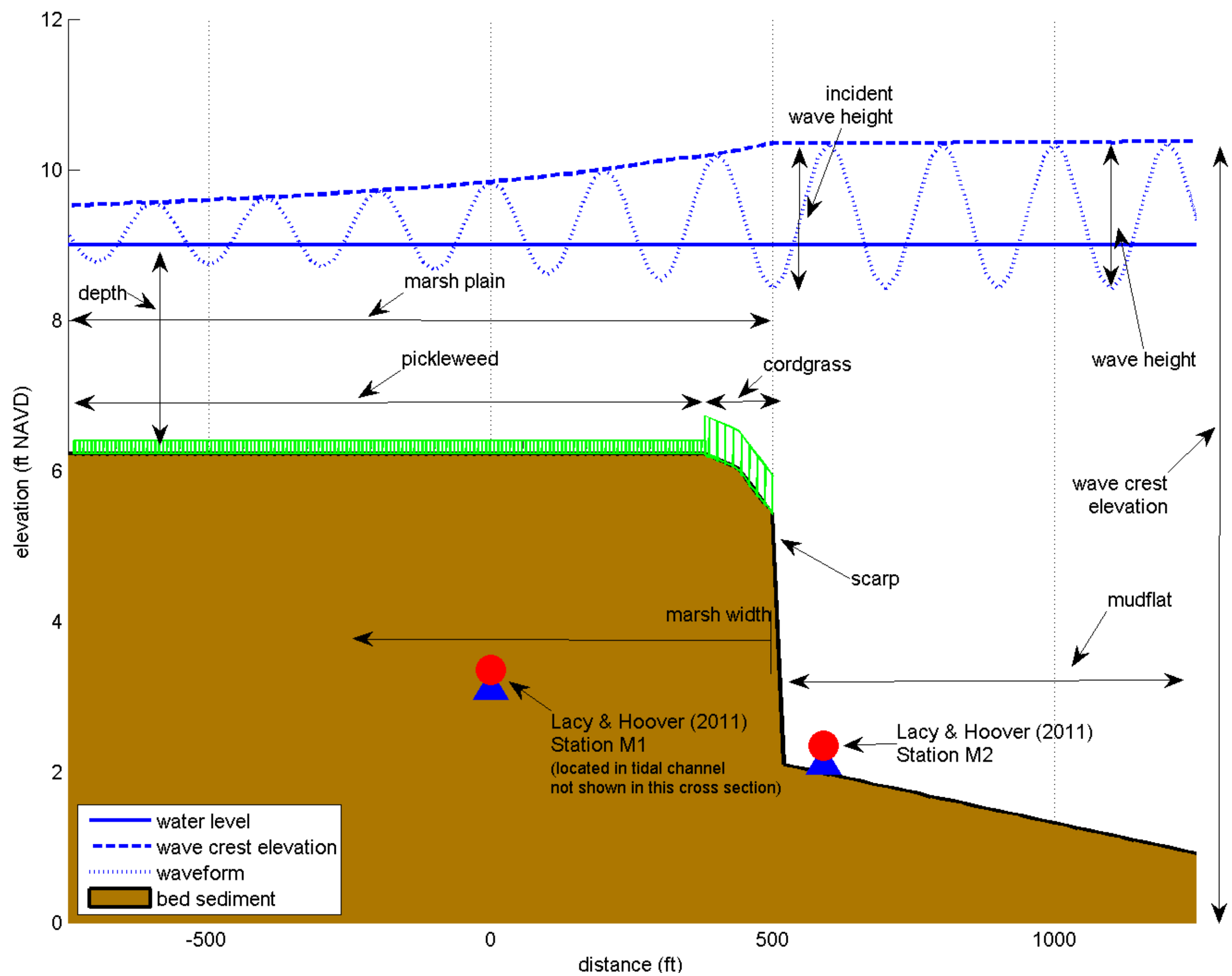
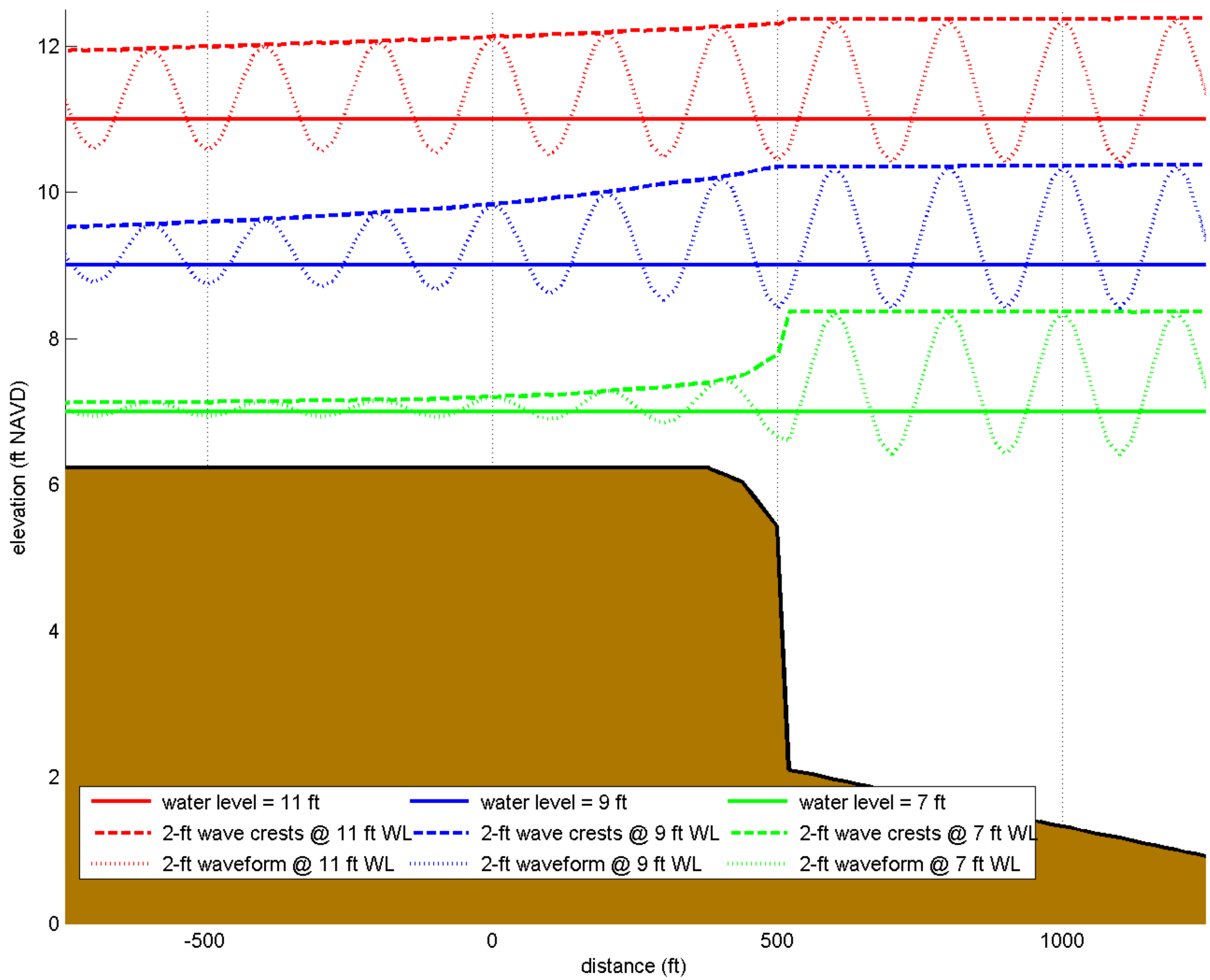


Figure 2. WHAFIS-predicted wave attenuation over marsh plain for water level of 7 ft, 9 ft, and 11 ft NAVD, wave height of 2 ft.



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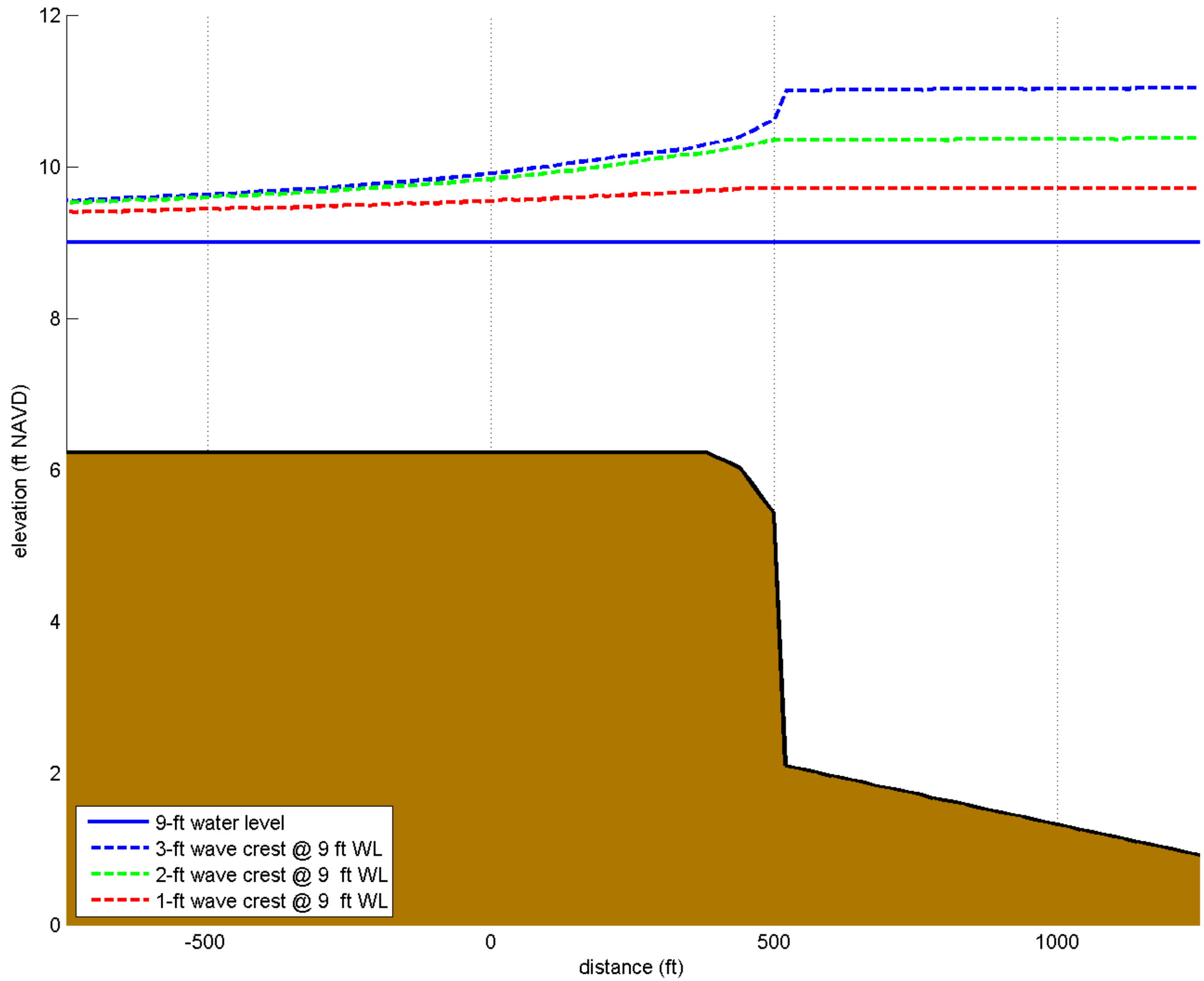


Figure 5. WHAFIS-predicted wave attenuation over existing scarp and modified slope bathymetry for water level of 7 ft and 9 ft NAVD, wave height of 2 ft.

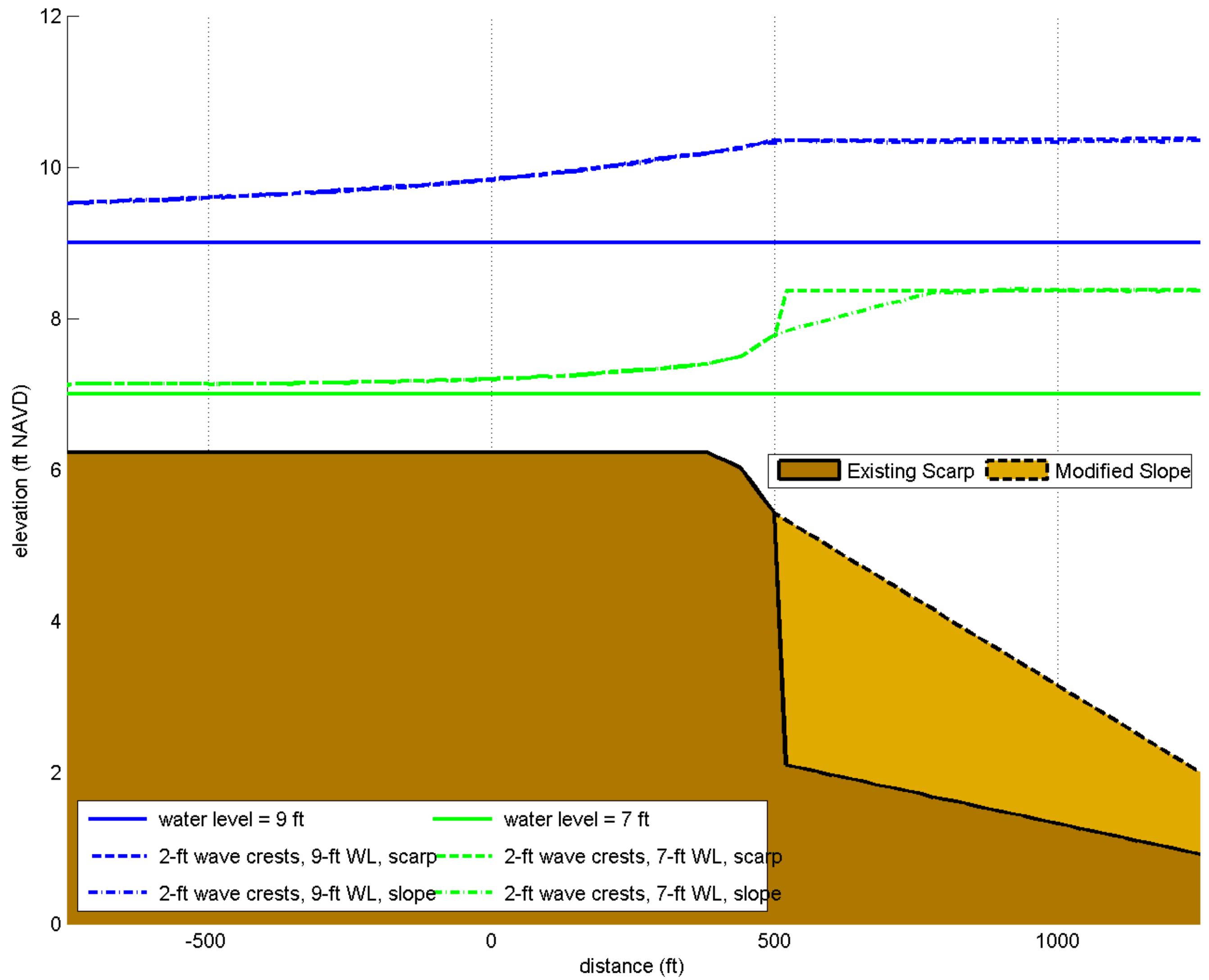
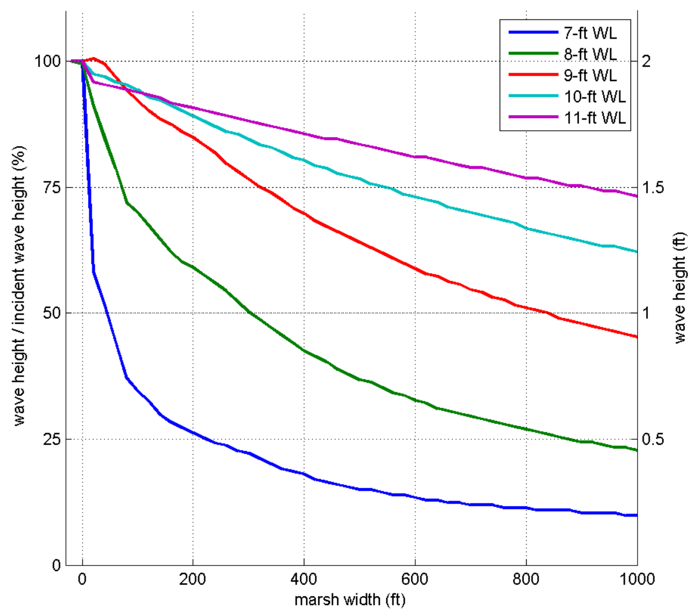


Figure 6. WHAFIS-predicted wave height relative to incident wave height as a function of marsh width, incident wave height equals (a) 2 feet, and (b) 3 feet.

a)



b)

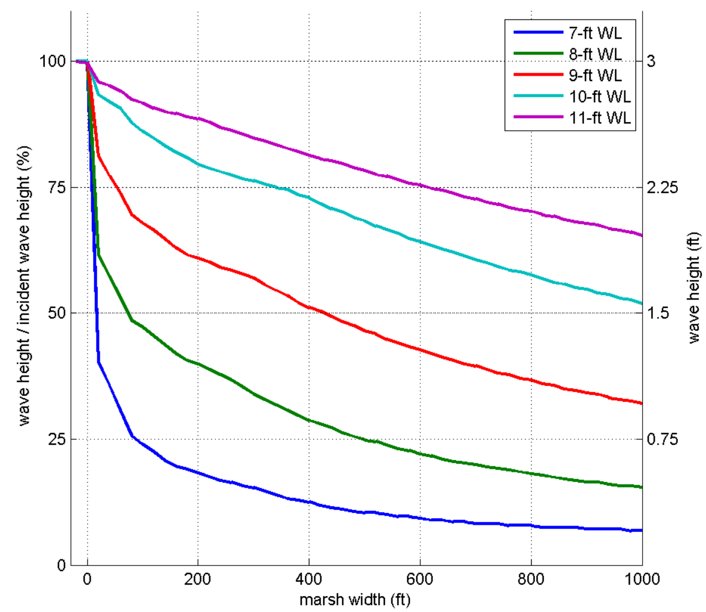


Figure 7. Comparison of WHAFIS and SWAN predicted wave height relative to incident wave height.